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6. AUTHOR(S)
Paul R. Berman, Tycho Sleator

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13. ABSTRACT (Maximum 200 words)
   The long range goal of this project was the creation of nanostructures using light fields to manipulate atoms. By passing an atomic beam through one or more standing wave light fields, it is possible to create modulations in the atomic density having periods which are a fraction of the period of the standing wave light fields. Patterns having periods as small as $\lambda/10$ were observed using optical masks and clear evidence for matter-wave effects were established. Several theoretical methods for achieving sub-λ matter wave patterns were developed. Moreover it was shown that it is possible to create optical lattices having reduced periodicity using Raman transitions in a novel atom-field geometry. Experiments were carried out in both magneto-optical traps and atomic beams. In both experimental set-ups, pulsed standing wave optical fields were used to excite the atoms. At some later time the atoms were probed by a traveling wave field, revealing the spatial pattterns that had evolved as a result of the atom-field interaction.

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I. ILLUSTRATION

Atomic density following two optical masks optical masks.

II. STATEMENT OF THE PROBLEM STUDIED

The problem studied in this project was a theoretical and experimental investigation of the potential application of atom-field interactions for creating nanostructures. In particular, schemes were developed that allow one to use optical radiation having wavelength λ to produce matter wave gratings having period $\lambda/2n$ where n is an integer greater than 2. A long term goal of the project, not realized in the current funding cycle, was the deposition of these nanostructures on a substrate. Methods for probing the density patterns with nanometer resolution were also explored, as were applications in atom interferometry. The research effort is a combined theoretical-experimental program, with the theory component housed at the University of Michigan and the experimental component at New York University.

This report covers the period 7/1/00-6/30/04. The principle results are summarized below. More detail can be found in previous annual interim progress reports and in reprints of articles published under support of this Grant.

III. SUMMARY OF IMPORTANT RESULTS

A. Theory

Several theoretical proposals were developed for creating and probing sub-λ matter wave gratings.

- A new type of pump-probe spectroscopy was reported [1] for carrying out pump-probe spectroscopy on a ground-state Raman transition in a thermal vapor. The pump and probe fields each consist of a *pair* of optical fields that drive a Raman transition. Not only do all the analogues of conventional non-linear spectroscopy exist for such a system, but new interference effect were also found occur. Moreover the line widths involved in this spectroscopy are much narrower than those of optical transitions, limited only by the effective decay rate of the ground state sublevels involved in the Raman transition.

- A careful analysis of large angle beam splitters was undertaken [2]. It was found that, although such beam splitters do separate atoms into widely separated velocity classes, the existence of more than two velocity classes degrades any matter wave gratings that are formed by such a beam splitter. As such, the underlying period of such beam splitters is $\lambda/2$ rather than $\lambda/2n$, as desired. Alternative methods involving interactions with *two* pairs of standing wave fields (similar to a compound lens) increase then fidelity of the gratings [3, 4].

- One of the most important findings was the possibility, *in a single interaction zone*, to create matter wave gratings that are a fraction of an optical wavelength, without any restrictions imposed by excited state lifetimes [5]. A novel Raman geometry is used in which a *pair of Raman fields* is used to drive a Raman transition. Each Raman field itself is composed of a pair of counterpropagating traveling wave fields. The Raman field act as a *standing wave Raman field* and reduce the basic periodicity of the problem from $\lambda/2$ to $\lambda/4$. Moreover, by a proper choice of field polarizations, the basic periodicity for total sub-level populations can be reduced to $\lambda/8$. In this manner one creates optical potentials having period equal to $\lambda/8$ [6]. Calculations have been completed to show that a new type of sub-Doppler cooling also exists for this atom-field geometry. An experiment is under way to test the theory. The techniques can be extended to a *multicolor* Raman geometry that will allow for further reduction of the periodicity.

- Large angle beam splitters resulting from inhomogeneous static fields were also investigated as a means for scattering into a narrow momentum wave packet. [7]. The beam splitter we proposed consists of a magnetic quadrupole and a homogeneous bias magnetic field. This combination of fields produces a scattering potential having a spatially homogeneous gradient near the center of the quadrupole, while outside of this region the potential is still non-linear. For a beam of ^{87}Rb atoms, a quadrupole size $a = 1$ cm, and a target grating period $\lambda_g = 100$ nm, and requiring the corrections to be not larger than 10%, we found that the beam velocity u,

the beam radius b, the half-thickness of the acceleration zone d, and the magnetic field gradient B' have to be chosen as $u \approx 16$ m/s; $b \approx 88\mu$; $d \approx 0.34$ cm, $B' \approx 170$ G/cm.

- A large angle beam splitter based on Bragg scattering using chirped laser fields was also considered [8]. The chirped field sequentially brings into resonance a chain of transitions in a Bragg ladder. Calculations for a beam having zero angular divergence indicate that the method is robust and can easily produce a 50-50 beam splitter with high efficiency. Momentum transfers as large as $50\hbar k$ can be realized with modest laser power. The angular divergence of the beam is the critical limiting factor; however, with proper state preparation, it is still possible to get sufficient flux for applications.

B.   Experiment

1.   Higher harmonics in a magneto-optical trap

Experiments are carried out in the time domain in a magneto-optical trap (MOT). During the funding period, sub-λ resolution of matter wave gratings was demonstrated using both optical phase and amplitude grating pulses to excite the atoms. Off-resonant optical fields were used in an echo sequence to create higher harmonic matter wave gratings [9]. Gratings having spacing $\lambda/2$ could be detected using conventional Bragg scattering, but gratings having smaller periods do not coherently back-scatter the laser radiation. A novel three-pulse echo scheme was used to detect gratings having period of $\lambda/4$. This was the first such direct observation of gratings of this type.

Most of the work during the funding period was concentrated on amplitude rather than phase gratings. To create an amplitude grating, an *optical mask* was used consisting of an optical standing wave pulse applied to a laser-cooled atomic cloud. The frequency of the mask pulse is made resonant with the $F = 3$ to $F' = 3$ transition ($5S_{1/2}$ to $5P_{3/2}$) in ^{87}Rb. The excited $F' = 3$ hyperfine state can decay to the $F = 2$ ground hyperfine state (as well as the $F = 3$ ground state) allowing a net loss of atoms from the initial $F = 3$ ground state hyperfine level. Such a pulse can be thought of as producing an atomic periodic structure, in that all atoms *not* at the nodes of the standing wave will be pumped into the $F = 2$ hyperfine level, and effectively lost.

The optical mask pulse can also be used to *image* a periodic atomic structure. Measurement of the total population of atoms remaining in the $F = 3$ state after an optical mask pulse gives the number of atoms that were at the positions of the standing wave nodes immediately before the pulse. (The total population can be measured by recording the fluorescence from a resonant traveling wave field). By performing a sequence of experiments, each with a different position of the imaging mask pulse, one can map out the atomic density distribution. Using a sequence of two masks (one for production of the matter wave amplitude grating and one for its detection), we find that density peaks having widths of order $\lambda/15 \approx 50$ nm were created by the optical mask [10].

If one applies two optical mask pulses separated by time T, one would expect to see atomic structure with period $\lambda/2n$ at times $(n + 1)T/n$ after the first pulse. This is analogous to echo formation in coherent transients. We have observed gratings with period as small as $\lambda/10 = 78$ nm in our experiments. Examples are shown in Fig. **??**(a) - (c).

If we choose T to be greater than the Talbot time (which is the inverse of the recoil frequency), then quantum effects play an important role in the resulting atomic structures. For example, with appropriate values of the pulse separation T, we have observed structures with period $\lambda/4$ and $\lambda/6$ at times $2T$ after the first mask pulse, as shown in Fig. **??**(d) - (e). Classically, one would only expect to see structures of period $\lambda/2$ at this time. These results represent an observation of the *Talbot-Lau effect*, also illustrated by the differences in Figs. **??**(b),(f). The differences are a direct manifestation of quantum, matter-wave effects.

2.   Beam Experiments

Experiments were carried out on one-dimensional transverse cooling of the atomic beam. The degree of cooling was determined by time-of-flight measurements of the velocity distribution. These measurements were made by imaging the fluorescence from the atomic beam downstream from the cooling region to get the size of the beam. The results of these experiments indicate that significant cooling is taking place. Typical parameters are a beam velocity of about 500 m/s, with a longitudinal spread of about 40% (full width at half max). Typical densities were about 10^8 atoms/cm^3 at 1 meter from the source, and atomic fluxes of about 5×10^{12} atoms/second. Although a smaller transverse velocity spread should result in a *magnetic grating free induction decay* (MGFID) signal of longer duration, no such effect was observed. We were unable to get a MGEcho signal which is one of the goals of the project.
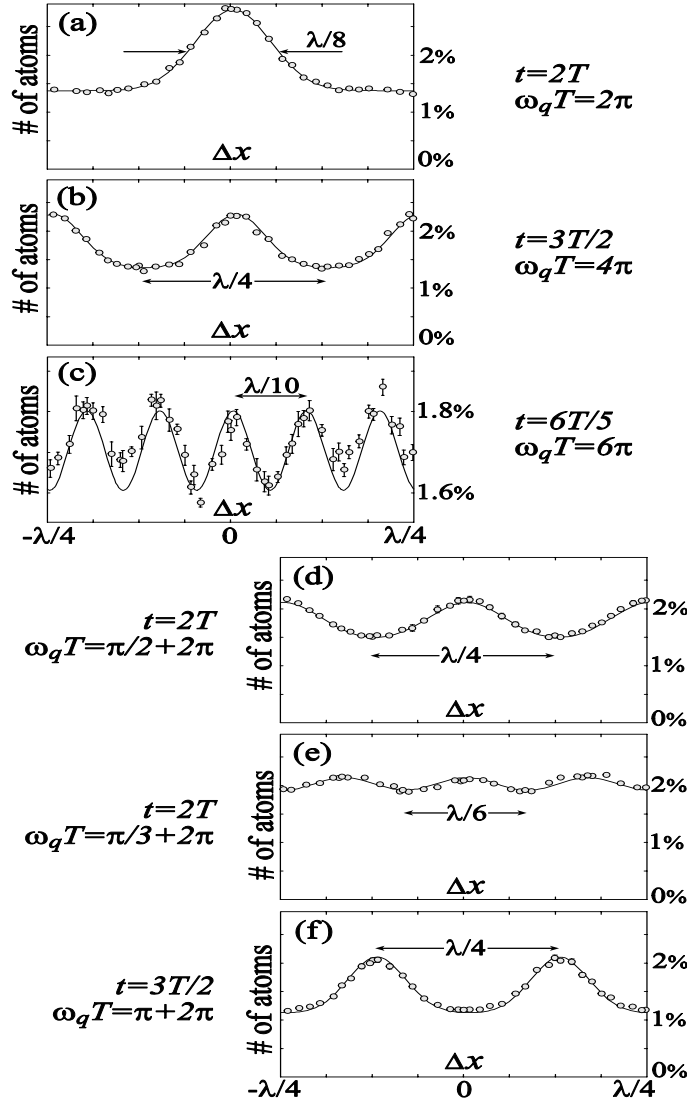
FIG. 1: Images of atomic density generated with the Talbot-Lau effect: (a) - (c) is the atomic density measured at varous times. (d) and (e) shows the atomic density measured at $t = 2T$ for different values of the recoil phase $\omega_q T$. The difference between these curves and those of (a) are due to matter-wave interference. (f) shows a shift the position of the maxima compared to (b) due to matter-wave interference. Open circles are data and the solid lines are fits.

C. Miscellaneous

Several other calculations have been carried out. In collaboration with the group of M. Pinard in France, we have shown that spin squeezing can be achieved on Raman transitions for atoms coupled to a cavity field [11]. Both self squeezing (coupling to a coherent state of the field) and squeezing transfer (coupling to a squeezed state of the field) were analyzed. Moreover, we found that, if the ground state coherence is pumped via additional fields, the spin squeezing that can be obtained is increased dramatically [12]. A fundamental calculation of spin squeezing for atoms coupled to a cavity mode without any losses was completed [13]. Somewhat surprisingly, even in the limit of an intense coherent state for the cavity field, spin squeezing occurs despite the fact that spins squeezing cannot occur for a *classical* field. As long as the number of atoms in the cavity is of the order of the number of photons in the field, quantum aspects of the field remain important. A calculation of the Goos-Hachen effect in negatively refractive media was completed [14]. It was also shown that a proposed scheme for suppression of spontaneous emission is fundamentally flawed [15]. In collaboration with P. Milonni at Los Alamos, we investigated the modification of the decay rate of an impurity atom embedded in a dielectric medium [16]. There has been some controversy concerning

the modified decay rate and we were able to resolve this problem using a microscopic approach in calculating the decay rate. This was a fundamental calculation that should shed some light on this problem. Currently we are extending the calculation to higher orders in the dielectric density to compare our results with "exact" polariton models. We have also provided theoretical support for an experiment on a "dipole blockade" using Rydberg atoms, having implications for storage of quantum information [17] With S. Malinovskaya, we have investigated methods for coherent control of selective excitation of closely spaced molecular vibrational transitions [18, 19]. Together with Richard Brewer, PRB wrote a chapter on Coherent Transients for the *Encyclopedia of Modern Physics* [20].

IV.   PUBLICATIONS

A.   Manuscripts published in peer-reviewed journals

1. P. R. Berman and B. Dubetsky , "Nonlinear ground-state pump-probe spectroscopy," Phys. Rev. A **62**, 053412 1-8 (2000).

2. C. P. Search and P. R. Berman, "Transferring the atom statistics of a Bose-Einstein condensate to an optical field," Phys. Rev. A **64**, 043602 1-7 (2001).

3. B. Dubetsky and P. R. Berman, "Asymptotic atomic gratings produced by a large angle beam splitter," Phys. Rev. A , **64**, 063612 1-13 (2001).

4. B. Dubetsky and P. R. Berman, "Spectrum of light scattering from an extended wave packet," J. Mod. Optics, **49**, 55-59 (2002)

5. D.V. Strekalov, A. Turlapov, A. Kumarakrishnan, and T. Sleator, "Periodic structures generated in a cloud of cold atoms", Phys. Rev. A **66**, 023601 (2002).

6. B. Dubetsky and P. R. Berman, "$\lambda/4$, $\lambda/8$, and higher order atom gratings via Raman transitions," Laser Physics **12**, 1161-1170 (2002).

7. P. R. Berman, "Goos-Hänchen shift in negatively refractive media, Phys. Rev. E **66**, 067603 (2002).

8. B. Dubetsky and P. R. Berman, "$\lambda/8$-period optical potentials," Phys. Rev. A **66**, 045402 1-3 (2002).

9. A. Zh. Muradyan, A. A. Poghosyan, and P. R. Berman, "Theory of a compound, large angle atom beam splitter," Phys. Rev. A **68**, 033604 1-7 (2003).

10. V. S. Malinovsky and P. R. Berman, "Momentum transfer using chirped standing wave fields: Bragg scattering," Phys. Rev. A **68**, 023610 1-5 (2003)

11. A. Dantan, M. Pinard, V. Josse, N. Nayak, and P. R. Berman, " Atomic spin squeezing in a Λ system," Phys. Rev A **67**, 045801 (2003).

12. A. Dantan, M. Pinard, and P. R. Berman, " EIT-assisted atomic squeezing," Europ. J. of Phys. D**27**, 193-199 (2003).

13. Andrey Turlapov, Alexei Tonyushkin, and Tycho Sleator, "Optical mask for laser-cooled atoms," Phys. Rev. A **68**, 023408 (2003).

14. G. Genes, P. R. Berman, and A. G. Rojo, "Spin squeezing via atom - cavity field coupling," Phys. Rev. A **68,** 043809 1-10 (2003).

15. B. K. Teo, D. Feldbaum, T. Cubel, J. R. Guest, P. R. Berman, and G. Raithel, "Autler-Townes spectroscopy of the $5S_{1/2} - 5P_{3/2} - 44D$ cascade of cold ^{85}Rb atoms, Phys. Rev. A **68**, 053407 1-4 (2003).

16. P. R. Berman, "Comment on 'Spontaneous-emission suppression on arbitrary atomic transitions,'" Phys. Rev. Lett. **92**, 159301 1 (2004).

17. P. R. Berman, "Causality in field emission from an atomic dipole," Phys. Rev. A **69** 022101 1-6 (2004).

18. P. R. Berman and P. Milonni, "Microscopic theory of modified spontaneous emission in a dielectric," Phys. Rev. Letters **92**, 053601 1-4 (2004).

19. S. Malinovskaya, P. Bucksbaum, and P. R. Berman, "Theory of selective excitation in stimulated Raman scattering," Phys. Rev. A **69**, 013801 1-5 (2004).

B. Manuscript published on archive

1. P. R. Berman, "Is negative refraction, perfect focusing compatible with quantum mechanics?," quant-ph/0309196.

C. Papers presented at meetings but not published

1. G. Genes, P. R. Berman, and A. G. Rojo, "Spin squeezing," DAMOP meeting, Boulder, May, 2003.
2. P. Berman, "Sub-wavelength optical latices and Sisyphus cooling," DAMOP meeting, Boulder, May, 2003.
3. S. A. Malinovskaya, P. R. Berman, and P. H. Bucksbaum, "Coherent control of vibrational excitations by ultrafast pulse shaping," DAMOP meeting, Boulder, May, 2003.
4. B. K. Teo, D. Feldbaum, T. Cubel, J. R. Guest, P. R. Berman, and G. Raithel, "High resolution, non-linear spectroscopy of cold Rydberg atoms," DAMOP meeting, Boulder, May, 2003.

D. Manuscripts submitted but not yet published

1. P. R. Berman and Ruwang Sung, "Electrostatic potential of a uniformly charged conducting plane deformed to include a spherical cup," Phys. Rev. E, submitted.
2. B. Dubetsky and G. Raithel, "Nanometer scale period sinusoidal atom gratings produced by a Stern-Gerlach beam splitter," Phys. Rev. A, submitted.
3. P. R. Berman and R. G. Brewer, "Coherent transient spectroscopy in atomic and molecular vapors," *Encyclopedia of Modern Optics*, to appear.
4. S. A. Malinovskaya, P. H. Bucksbaum, and **P. R. Berman**, "On the role of coupling in mode selective excitation using ultrafast pulse shaping in stimulated Raman spectroscopy," J. Chem Phys., to appear.
5. P. R. Berman and P. Milonni, "Atom-field interactions with a frequency dependent reservoir," Phys. Rev. A, submitted
6. P. R. Berman, "Wigner-Weisskopf approximation under typical experimental conditions," Phys. Rev. A, submitted.
7. A. Zh. Muradyan, G.A. Muradyan, and P. R. Berman, "Theory of a compound, large angle atom beam splitter: II. Initial state beam splitter," Phys. Rev. A, submitted.
8. U. Shim, A. Kumarakrishnan, A.V. Turlapov, S. B. Cahn, and T. Sleator, "Collisional Revival of Magnetic Grating Free Induction Decay," Phys. Rev. A , submitted.
9. Andrey Turlapov, Alexei Tonyushkin, and Tycho Sleator, "Talbot-Lau effect for atomic de Broglie waves manipulated with light," Phys. Rev. Lett., submitted.

V. PARTICIPATING SCIENTIFIC PERSONNEL

Prof. P. Berman, Principal Investigator
Prof. B. Dubetsky, Associate Research Scientist
Prof. T. Sleator, Director of the Experimental program
Dr. V. Malinovsky, Postdoctoral Scientist
Andrey Turlapov, Graduate Student (PhD received)
Alexei Tonyushkin, Graduate Student

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